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The thrust of this research program is the improvement of our capabilities for analyzing stability and transition of boundary layers at supersonic speeds. During the previous reporting period, our efforts were primarily directed toward analytical studies, establishing the elements of the numerical approach, and evaluating existing and new concepts to tackle the variety of problems. This reporting period has been devoted to combining selected elements into codes, verification of these codes, comparison with previous results, and computing the basic flow over realistic geometries. The latter task has consumed the bulk of our resources. Analytical and numerical studies have been performed to investigate the role of the shock on both stability and receptivity characteristics of the flow. Development of the parabolized stability equations (PSE) has continued. A new code incorporating the latest concepts is largely completed.

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THE OHIO STATE UNIVERSITY

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Summary

The thrust of this research program is the improvement of our capabilities for analyzing stability and transition of boundary layers at supersonic speeds. During the previous reporting period, our efforts were primarily directed toward analytical studies, establishing the elements of the numerical approach, and evaluating existing and new concepts to tackle the variety of problems. This reporting period has been devoted to combining selected elements into codes, verification of these codes, comparison with previous results, and computing the basic flow over realistic geometries. The latter task has consumed the bulk of our resources. Analytical and numerical studies have been performed to investigate the role of the shock on both stability and receptivity characteristics of the flow. Development of the parabolized stability equations (PSE) has continued. A new code incorporating the latest concepts is largely completed.

1. Objectives

Our research program aims at deve! ,ing and applying theoretical, numerical, and graphical tools for the quantitative description and deeper understanding of stability and transition in supersonic boundary layers. In particular, the program aims at incorporating and analyzing the effects of nonparallelism, nonlinearity, and secondary instabilities on stability and transition. Toward these goals, we have worked in the following areas:

(1) Computation of the basic flow over sphere-cone combinations.

(2) Derivation of the nonlinear stability equations in general coordinates and computation of the derivatives from the basic flow.

(3) Shock boundary conditions and propagation of disturbances along shocks.

(4) Nonlinear parabolized stability equations (PSE) for supersonic flow, including mathematical and numerical aspects.

(5) General aspects of transition prediction and bypasses with emphasis on supersonic flows.

2. Achievements

We have made considerable progress in various areas yet have not achieved all the milestones set for this period. There are various reasons for these delays. The field of compressible flows has made relatively little progress over the past decades and much ground work must be done to prepare the basis for future progress. The literature is difficult to access and often only available in Russian or in unreliable translations. The formalism for compressible flows is voluminous and most steps require unexpectedly intense efforts to obtain a clean formulation with access to physical reasoning. Various published results, including recent results of Malik and coworkers lack the required rigor and cause tedious search for explanations and re-derivations. Numerical work on flows over realistic geometries in the past has been largely conducted to obtain surface data which may be in reasonable agreement with experiments. Accurate field computations necessary for stability analysis are unavailable and cannot be obtained with the numerical methods in common use (this conclusion agrees with the findings of Mack (1986)). Experimental work is insufficiently documented for theoretical analysis. Fortunately, we were able to clarify the results of Stetson and his co-workers in telephone discussions and through unpublished tables and graphs.

A second major difficulty is the long startup period required for students to become involved in this research. Both the area of stability and the area of supersonic flows are too complex to be covered in undergraduate or entry graduate courses to the extent necessary for this work. In addition, the work demands skills in symbolic manipulation, computation, and visualization. While the present team has good potential, the continuous intense advice imposes a heavy burden on the principal investigator.

The third reason for delay have been the tremendous efforts to develop and speed-up the code for computing an accurate basic flow and to obtain the necessary computer resources from the Ohio Supercomputer Center. The run time for a single field on a single Cray YMP processor amounts to a few hundred hours although the code performs near the theoretically possible speed. Since the code requires up to 50 Mwords of memory (our YMP has a total of only 64 Mwords for all eight processors), we are charged multiples of the actual CPU time and can run only at lowest priority. We have not yet reached the final station 250 nose radii downstream to cover the full range of the experiments of Stetson et al. (1984)

Some details on progress in the various areas of interest are reported below.

2.1. Computation of the Flow over Sphere-Cone Combinations.

The analysis of stability and transition requires the basic flow to be known. The stability characteristics depend not only on the flow variables but also on their first and partly on their second derivative normal to the boundary. Stability studies are usually performed for similarity solutions (e.g. Blasius) that can be calculated from ordinary differential equations with arbitrary accuracy. Flows over realistic geometries such as the sphere-cone combinations studied by Stetson et al. (1984), however, require solution of partial differential equations to obtain the overall flow field. The resolution is usually sufficient for calculation of the surface-pressure yet not for resolving the viscous boundary layer. We have spent intense efforts in this problem area and have evaluated the utility of numerical methods for solving the full Navier-Stokes equations (NS), thin-layer Navier-Stokes equations (TLNS), parabolized Navier-Stokes equations (PNS), viscous shock-layer equations, and boundary-layer equations. We have also evaluated the available TLNS codes to obtain blunt-body flows and their PNS continuation downstream. The efforts to compute a clean flow field with existing codes were useless. The TLNS codes converge only for a body length of the order of a few nose radii while we are interested in lengths of typically 150 to 250 radii where instabilities are observed in Stetson's experiments. The PNS continuation provides a field with jumps and wiggles (as reported by Malik et al.) unacceptable for stability analysis. The effect of these wiggles can be suppressed by removing terms from the stability equations. This drastic step (Malik et al.) is unacceptable, however, since it may affect the physics.

The traditional boundary-layer approach cannot be exploited because of the presence and crucial importance of the entropy layer. V. Esfahanian has therefore written a new TLNS code using the Beam-Warming method and shock fitting. The code has been extensively verified for the standard test case of a hemisphere-cylinder combination at Mach number 2.94 and for the blunt cone with 0.15 in nose radius and 7 degree half-angle at Mach number 8 (Stetson et al.). Numerous improvements to previous techniques have been made and the flow field can be obtained for the required region without encountering convergence failures. The computational demand, however, increases dramatically with the length of the body. A first run with a 1500 streamwise by 100 cross-stream grid provided results in good agreement with all theoretical benchmark data (sharp-cone flow, Euler solution, etc.) and with the experimental field of Stetson et al. However, as shown in figure 1, the cross-stream resolution was still insufficient to resolve the detail of the flow near the edge of the boundary layer - a region critical for the second-mode disturbances in the experiments. To make further improvements feasible, the code has been thoroughly vectorized and various routines run near the theoretically achievable speed. In return for these successful and exemplary efforts, the Ohio Supercomputer Center has awarded us in excess of 2200 resource units, the equivalent of about 700 CPU hours to perform runs at higher resolution. A first run on a 3000 by 200 grid was stopped before the solution fully converged owing to an unexplainable error message that meanwhile turned out to appear when a certain amount of CPU time is exceeded. The final output is reusable and can be converged if resources will still be available. A new run at 1500 by 200 is fully converged up to 200 nose radii and will be continued to the final station in the near future.

The effort and expense for these runs has been justified by the concerns discussed in the U.S. Transition Study Group at the meetings in Seattle 1990 and Reno 1991 that the stability results for supersonic flows over realistic bodies may be biased or flawed by the inaccuracies of numerical solution for the basic flow. The Study Group plans a detailed code comparison for computation of supersonic flows to remove the current uncertainty about the value of stability results for realistic flows. Our results have been generated with sufficient attention to every aspect that could affect the stability analysis to use them as a benchmark for evaluation of other methods.

Besides providing the basis for stability analysis, the flow field reveals the interesting physics caused by bluntness. The compression waves arising near the sphere-cone junction cause an inflection point in the shock further downstream, as shown in figure 2. The shock angle recovers to the inviscid sharp-cone value at about 150 radii. Further downstream, the angle is slightly larger owing to the viscous displacement effects. Visualizations of the flow quantities on color-graphics workstations reveals the extent of the entropy layer and the downstream propagation of the pressure disturbance caused by the abrupt change in curvature at the sphere-cone junction. The wall-pressure distribution is in excellent agreement with the measurements of Stetson et al. as shown in figure 3. The same holds for the shock shape as good as it can be read from schlieren photographs. In contrast, the wall temperature (figure 4) in the experiments deviates by about 15% from the computed values which assume an adiabatic wall. While this deviation is significant, it is not expected to change the stability characteristics drastically. Velocity distributions outside and in the outer parts of the boundary layer agree well between computation and experiment, as shown in figure 5. The lack of agreement closer to the cone is due to the size of the probe and increasing interference with the wall (Stetson, personal communication).

2.2. Stability Equations in General Coordinates

Previous work has either neglected or only partially accounted for the curvature effects on basic flow and stability characteristics. While the step-by-step inclusion of curvature in previous work has provided the opportunity for follow-up publications of minor value, we have decided to account for the curvature terms completely and from the beginning. We have derived the nonlinear stability equations including transverse and longitudinal curvature as functions of the distance from the wall. The linearized equations have been coded for use with both spectral method or compact finite-difference method. The coded insert files are consistent with the file format used by the stability code linear.x (Herbert 1990).

Various procedures have been coded and compared to obtain the metric terms and flow quantities as well as their derivatives as accurately as possible. This task is nontrivial since the finite-difference method is only of second order in space. There are certain trade-offs between spectral and compact treatment of the stability problem. The spectral method is advantageous by requiring lower derivatives than the 4th-order compact scheme. The compact scheme, however, can utilize the data at the grid points directly while the spectral method uses less points in a different distribution. Suitable procedures have been developed for both cases since the spectral method is far superior for calculating eigenvalue spectra needed to identify the complete set of unstable modes. The compact finite-difference method, however, is more efficient for tracing a specific mode over variable parameters.

In general, our results for the test cases discussed by Malik (1990), and conclusions regarding the accuracy achievable with a given number of polynomials or grid point differ from Malik's. We suspect that Malik's spectral codes suffer from round-off errors. All our stability results have been cross-checked between different numerical methods and different codes.

While the stability analysis for flow of Stetson et al. is not yet completed, the results for station 175 allow already some major conclusions. Figure 6 compares the experimental results for the spatial growth rates with the theoretical results of Malik et al. (1990) for the first and second mode and our results (for the second mode only). Although both theoretical studies are for the computed blunt-body flow and include boundary conditions at the shock, the results are remarkably different. The difference is due to various approximations introduced in the work of Malik et al., which include the neglect of the mean pressure variation, the neglect of the difference between the flow parallel to the computational grid and the flow parallel to the wall, use of the PNS instead of the TLNS equations, and others. A detailed analysis cannot be made since basic flow and stability procedures of Malik et al. are insufficiently documented.

Remarkable is the discrepancy between the experimental and theoretical results for the blunt cone. In fact, the theoretical blunt-cone results are quite similar to the sharp-cone results of Mack (1987). Mack provides some explanation for the difference between the data in this figure which can also be applied to the blunt-cone experiment. The theoretical results, however, give no clue why sharp-cone (Stetson et al. 1983) and blunt-cone (Stetson et al. 1984) experiments exhibit different local stability characteristics.

Our analysis has revealed various weaknesses of the traditional stability theory in context with the flow studied here. The flow is certainly not parallel and the role of the nonparallelism inside and outside the boundary layer has not yet been investigated. Also, the implementation of the boundary conditions at the (oblique) shock causes difficulties and loss of physical impact. The history of the disturbances cannot be studied with the local analysis. The absence of the theoretically predicted cut-off frequency for instability may indicate elimination of branch II by nonlinear effects, as it occurs in incompressible boundary layers. This hypothesis, though not yet substantiated by quantitative analysis, is in line with Stetson's discussion of nonlinear effects.

We currently analyze the neutral curve for first and second modes in the computed basic flow. If this analysis verifies the observed increase of the critical Reynolds number, the more pronounced nonlinearity of disturbances in the blunt-cone flow should be caused by increased receptivity - provided the experimental environment has been the same as for the sharp-cone runs. We will continue to search for the source of the different transitions observed for sharp and blunt cones. It appears, however, that in absence of an independent verification of the observed facts (Guideline No. 4 of the U.S. Transition Study Group) this search will not lead to clear physical conclusions without filling deep gaps in our understanding of high-speed transition by theoretical and numerical results.

2.3. The Disturbed Shock

The presence of a shock as the outer boundary of the shear flow is a major difference from the situation at subsonic speeds. This difference becomes more pronounced as the Mach number increases. The shock shape for sharp and blunt cones is different up to about 150 nose radii where instability occurs. Further, shocks are not as steady as they appear in the short-time exposed schlieren photographs. Disturbances impacting the shock lead to shock corrugations that are associated with entropy and pressure waves. Local disturbances of the shock propagate along the shock. Disturbances may exist inside the shock layer or in the free stream. In both cases, we are faced with a receptivity problem rather than a traditional stability issue. We have studied various aspects of the shock corrugation.

We have derived and analyzed the boundary conditions at the shock from the generalized Rankine-Hugoniot conditions. The linearized conditions have been implemented in a study of the temporal instability of the viscous flow over a wedge with adiabatic wall at Mach number 8. The growth rate of the second mode is affected in two ways, first by the finite domain between wall and shock, second by the different boundary conditions. Both effects cause a moderate stabilization at small wave numbers as shown in figure 7. The growth rate near maximum amplification, however, remains unchanged. Considered the propagation of information along (unsteady) characteristics, the local stability analysis can capture only a part of the physics near the shock. We have studied various models to find better ways of accounting for the effect of the shock. Starting from the corrugation instability of plane shock waves (see Landau & Lifshitz 1959), we have attempted to analyze the propagation of disturbances along oblique shocks. This study is in progress but has not yet led to conclusive results.

2.4. Parabolized stability equations (PSE) for supersonic flow

The work on extending the concept of parabolized stability equations (Herbert & Bertolotti 1987, Bertolotti, Herbert & Spalart 1990) to supersonic flows has continued. A first report on linear first-mode disturbances is under review for publication (Bertolotti & Herbert 1990). After F. Bertolotti has joined Princeton University (Orszag & Karniadakis) as a post-doctoral associate in September 1990 (although his graduation is still pending), we are in the process of building a new group with expertise in this promising area. Numerical difficulties with single-domain spectral methods encountered at higher Mach numbers in Bertolotti's work have been overcome. In addition, we have further developed the two-domain spectral method (Hartonas 1990) and successfully applied second- and fourth-order compact method to the local problem. We are in the process of implementing these techniques in a new version of the marching code. This new modular version is compatible with the linear stability code linear.x and fully integrates the setup of initial conditions for different models of transition.

Various theoretical studies have been conducted to shed light on the mathematical structure of the PSE approach. The results have led to significant improvements in formulating the method and in the algorithms for solving the system of nonlinear equations. These studies also concern the extension of the PSE approach to three-dimensional boundary layers.

Additional work in the supersonic area is supported by WPAFB under Contract No. F33615-90-C-3009 with DynaFlow, Inc. This work aims at developing the PSE approach as an engineering method for transition prediction.

2.5. Transition Analysis and Prediction

With the forthcoming capabilities for efficient simulation of the transition process under given initial conditions, we have performed a systematic analysis of the problem areas and requirements for transition prediction in engineering design. An overview of this work has been given as an invited talk at the AIAA 28th Aerospace Sciences Meeting, Reno, Nevada, January 1991 (AIAA Paper No. 91-0737). A more complete version of this paper will be prepared for publication.

In the past, the critical evaluation of transition prediction (by Morkovin, Reshotko, and others) under the aspects of linear results for parallel flows and the inability to tackle the nonlinear problem has created a negative image of attempts for improvements and wide-spread confusion about realistic expectations. It appears important that this bias be removed before broader interest can create the demand and support for more powerful engineering tools that would justify the training of a qualified work force. The presentation and paper at the AIAA meeting have been a first step in this direction. The cleanup and reorganization of Morkovin's "pathways to turbulence" into the "systems view of transition" in figure 8 has been a second step that found the approval of the "experts." A slightly different version of figure 8 will be published in Morkovin's contribution to the ASME Symposium on boundary-layer stability in Oregon, 1991 (my contribution to this symposium was canceled since ASME did not accept the camera-ready manuscript except on the antique large mats that I cannot process with my equipment). A detailed block-by-block and line-by line description of the issues indicated in figure 8 is in preparation. We have also started to apply the PSE technique to forced problems to evaluate the chance for resolving some of the bypass problems that may interfere with an otherwise correct design. The ability to incorporate both initial conditions and inhomogeneous boundary conditions into the PSE approach makes this method suitable not only for inexpensive transition simulations and as a replacement for the commonly used $e sup N$ method, but also as an engineering method for advanced design. Such methods can be very useful in evaluating environmental (wind tunnel vs. free flight) effects on concepts such as hybrid laminar flow control.

Our efforts so far have awakened encouraging interest of commercial airplane companies in longer-term cooperation and support of further research and development toward engineering applications of the PSE.

3. Personnel

The following personnel has participated in the work and has been partially supported under this contract:

Th. Herbert, principal investigator

Fabio P. Bertolotti, PhD student

Vasiliki Hartonas, MS student

Vahid Esfahanian, PhD student

Ron Bayless, MS student

Mengjie Wang, PhD student

Charlotte Hawley, Systems Programmer 2

V. Hartonas has received her M.S. in June 1990. F. P. Bertolotti has completed all technical requirements for his Ph.D. and has been working since September 1990 as a post-doctoral associate with S. A. Orszag and G. Karniadakis at Princeton University. His graduation is delayed due to his non-compliance with some regulations of the graduate school. V. Esfahanian has almost completed his thesis on computation and stability analysis of the flow over sphere-cones and will receive his Ph.D. at the end of March 1991. R. Bayless studies the stability of shock waves and will graduate in Spring 1991. M. Wang cooperates in the studies on nonparallel flows in preparation for work on the PSE code.

4. Publications

The following publications were completed or originated from work under support by this contract:

"Comparing Local and Marching Analyses of Görtler Instability," by H. P. Day, Th. Herbert, and W. S. Saric, *AIAA J.*, Vol. 28, pp. 1010-1015 (1990).

"Threshold Conditions for Breakdown of Laminar Boundary Layers," by Th. Herbert and J. D. Crouch, in: *Laminar Turbulent Transitions,* Editors D. Arnal and R. Michel, pp. 93-101, Springer-Verlag (1990).

"Theory of Instability and Transition," by Th. Herbert, in: *Instability and Transition, Vol. I,* (Eds.) M. Y. Hussaini, R. G. Voigt, pp. 20-31, New York: Springer-Verlag (1990).

"Linear.x - A Code for Linear Stability Analysis," by Th. Herbert, in: *Instability and Transition, Vol. II,* (Eds.) M. Y. Hussaini, R. G. Voigt, pp. 121-144, New York: Springer-Verlag (1990).

"Transition Analysis with Parabolized Stability Equations," by Th. Herbert and F. P. Bertolotti, *Bull. Am. Phys. Soc.,* Vol. 35, pp. 2230 (1990).

"Fast Simulations of Boundary-Layer Transition with PSE," by F. P. Bertolotti and Th. Herbert, *Bull. Am. Phys. Soc.,* Vol. 35, pp. 2230 (1990).

"Nonlinear Evolution of Secondary Instabilities in Boundary-Layer Transition," by J. D. Crouch and Th. Herbert, *J. Fluid Mech.* (1990), submitted for publication.

"Linear and Nonlinear Stability of the Blasius Boundary Layer," by F. P. Bertolotti, Th. Herbert, and P. R. Spalart, *J. Fluid Mech.* (1990), submitted for publication.

"Boundary-Layer Transition - Analysis and Prediction Revisited," by Th. Herbert, AIAA Paper No. 91-0737 (1991).

"Exploring Transition by Computer," by Th. Herbert, *J. Appl. Num. Math.,* Vol. 7, No. 1, pp. 3-27 (1991).

5. Technical Presentations

"Stability of Ncnparallel Shear Flows," invited lecture, by Th. Herbert, NATO Advanced Research Workshop Euromech 261 "Colloquium on Görtler Vortex Flows," Nantes, France (June 1990).

"Simulation of Boundary-Layer Transition with Parabolized Stability Equations," by Th. Herbert, IMACS 1st Int. Conf. on Computational Physics, Boulder, Colorado (June 1990).

"Linear Stability of Compressible Planar Couette Flow," by G. Erlebacher and Th. Herbert (presented), IMACS 1st Int. Conf. on Computational Physics, Boulder, Colorado (June 1990).

"Spatial Evolution of Boundary-Layer Transition," by Th. Herbert, Dept. Mathematics, MIT, Cambridge, Massachusetts (October 1990)

"Transition Analysis with Parabolized Stability Equations," by Th. Herbert, NASA Lewis Research Academy, Cleveland, Ohio (November 1990).

"Transition Analysis with Parabolized Stability Equations," by Th. Herbert and F. P. Bertolotti, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Cornell University, Ithaca, New York (November 1990).

"Fast Simulations of Boundary-Layer Transition with PSE," by F. P. Bertolotti and Th. Herbert, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, Cornell University, Ithaca, New York (November 1990).

"Boundary Layer Transition - Analysis and Prediction Revisited," invited lecture, by Th. Herbert, AIAA 29th Aerospace Sciences Meeting, Reno, Nevada (January 1991).

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Bertolotti, F. P. & Herbert, Th. 1990 "Analysis of the Linear Stability of Compressible Boundary Layers using the PSE," *J. Theor. Comp. Fluid Mech.*, submitted for publication.

Bertolotti, F. P., Herbert, Th., & Spalart, P. R. 1990 "Linear and Nonlinear Stability of the Blasius Boundary Layer," *J. Fluid Mech.*, submitted for publication.

Herbert, Th. 1990 "Linear.x - A Code for Linear Stability Analysis," in: *Instability and Transition, Vol. II,* (Eds.) M. Y. Hussaini, R. G. Voigt, pp. 121-144, New York: Springer-Verlag (1990).

Herbert, Th. & Bertolotti, F. P. 1987 "Stability Analysis of Nonparallel Boundary Layers," *Bull. Amer. Phys. Soc.*, Vol. 32, p. 2079.

Landau, L. D. & Lifshitz, E. M. 1959 *"Fluid Mechanics,"* Pergamon Press.

Mack, L. M. 1986 "Boundary-layer stability analysis for sharp cones at zero angle of attack," AFWAL-TR-86-3022, Flight Dynamics Laboratory AF Wright Aeron. Laboratory.

Mack, L. M. 1987 "Stability of axisymmetric boundary layers on sharp cones at hypersonic Mach numbers," AIAA Paper No. 87-1413.

Malik, M. R. 1990 "Numerical methods for hypersonic boundary layer stability," *J. Comp. Phys.*, Vol. 28, pp. 376-413.

Malik, M. R., Spall, R. E., & Chang, C.-L. 1990 "Effect of nose bluntness on boundary layer stability and transition," AIAA Paper No. 90-0112.

Stetson, K. F., Thompson, E. R., & Donaldson. J. C. 1983 "Laminar boundary layer stability experiments on a cone at Mach 8, Part 1: Sharp cone," AIAA Paper No. 83-1761.

Stetson, K. F., Thompson, E. R., Donaldson. J. C., & Siler, L. G. 1984 "Laminar boundary layer stability experiments on a cone at Mach 8, Part 2: Blunt cone," AIAA Paper No. 84-0006.

Figure 1. Comparison of density profiles for a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3^o$ K at station S/R_N = 175 (Stetson et al.) for different grids normal to the wall.

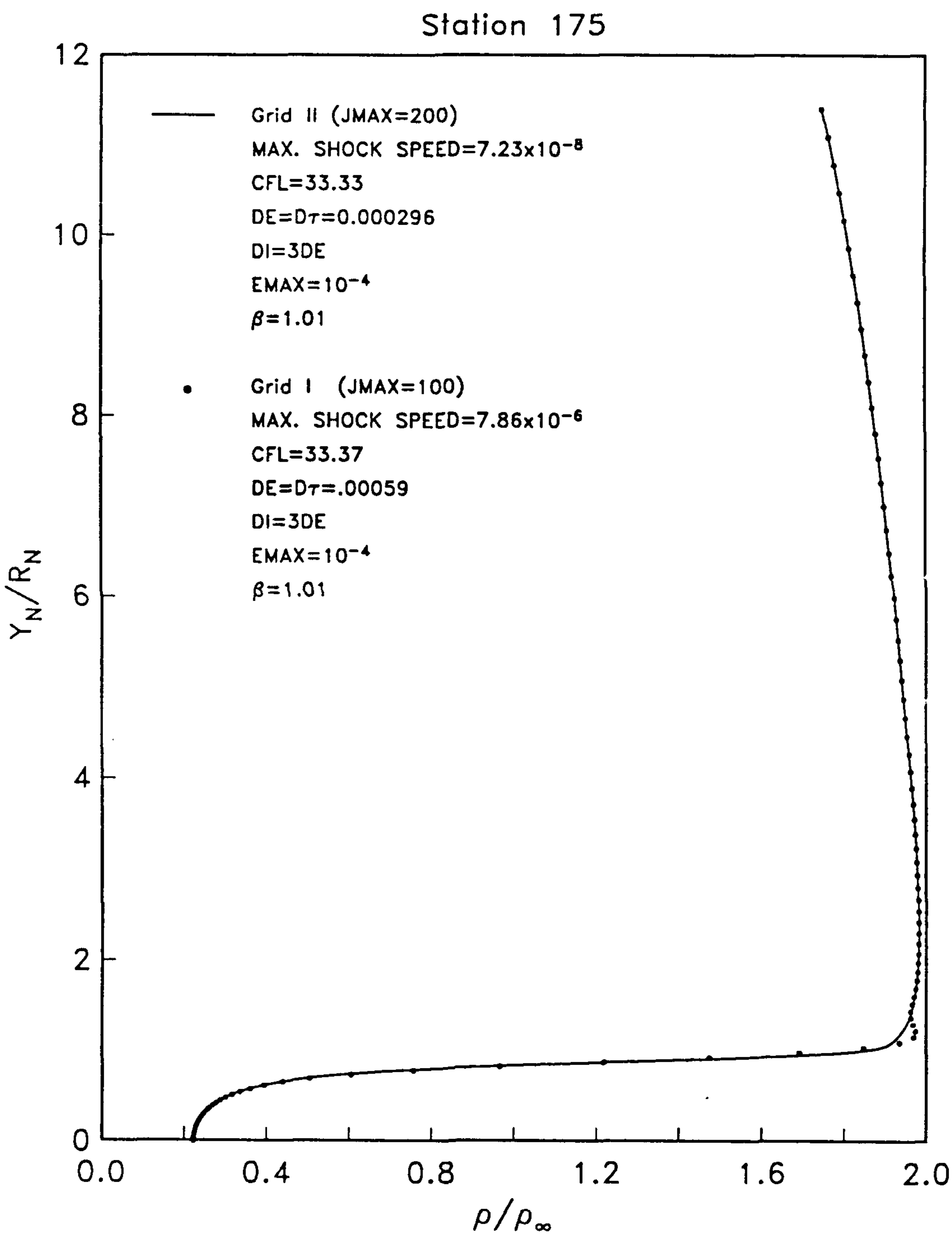
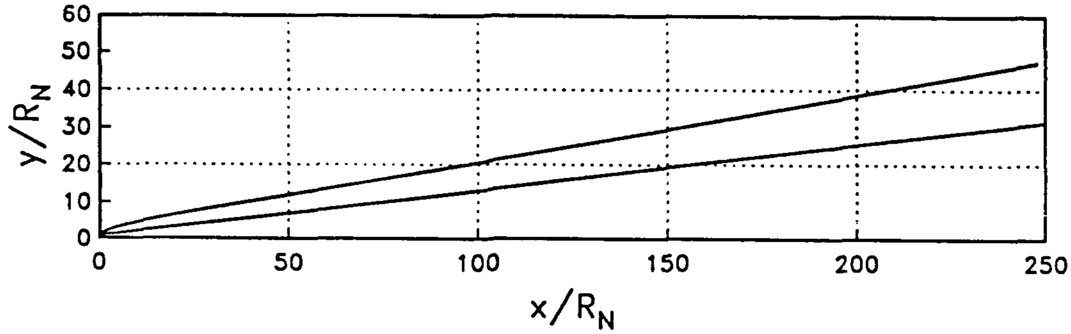


Figure 2. Shock shape (top) and shock angle (bottom) for the flow on a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3^o$ K up to station $S/R_N = 250$ (Stetson et al.)



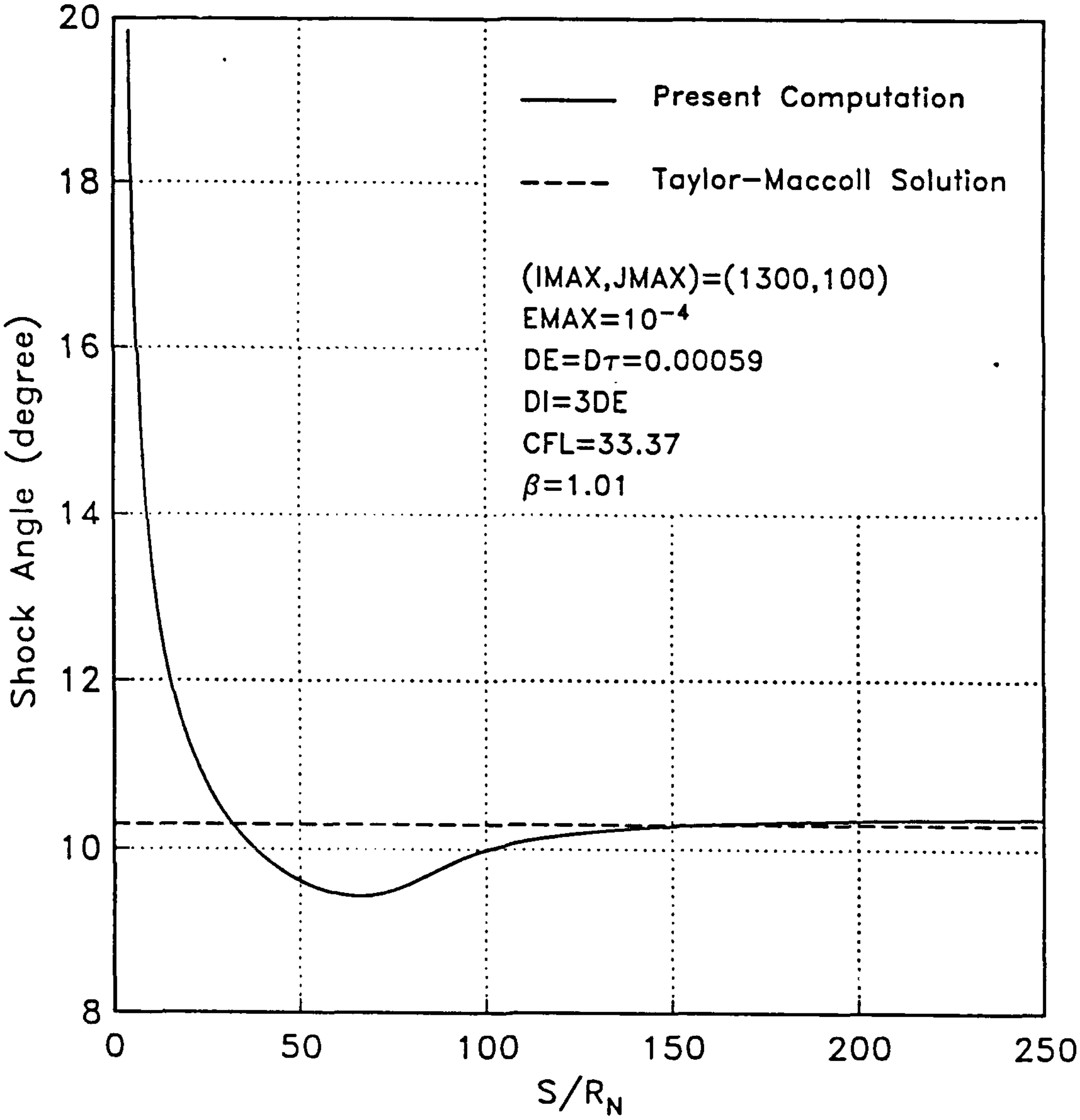


Figure 3. Comparison of the surface pressure distribution for a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3°$ K with experimental data of Stetson et al.

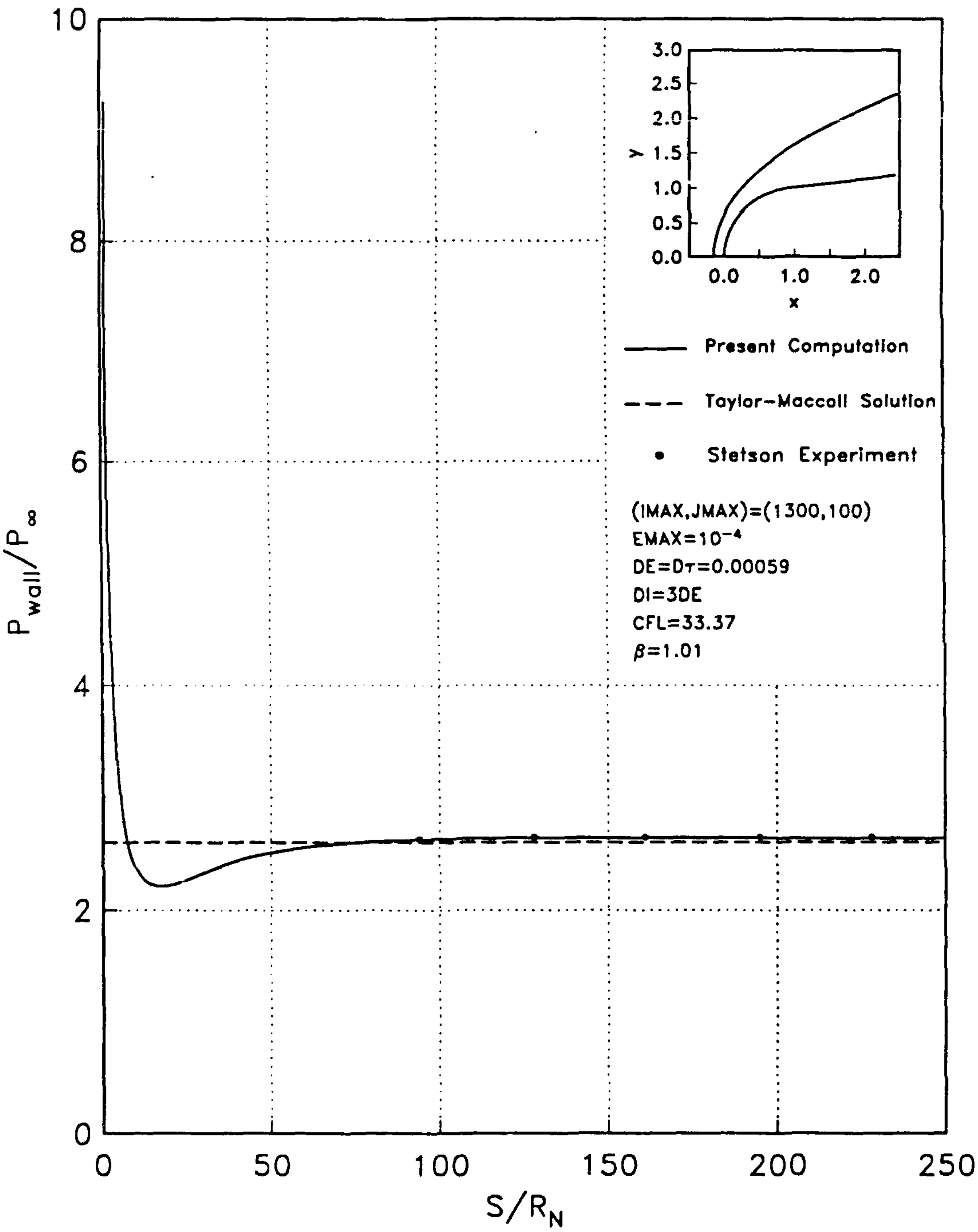


Figure 4. Comparison of the surface temperature distribution for a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3°$ K with experimental data of Stetson et al.

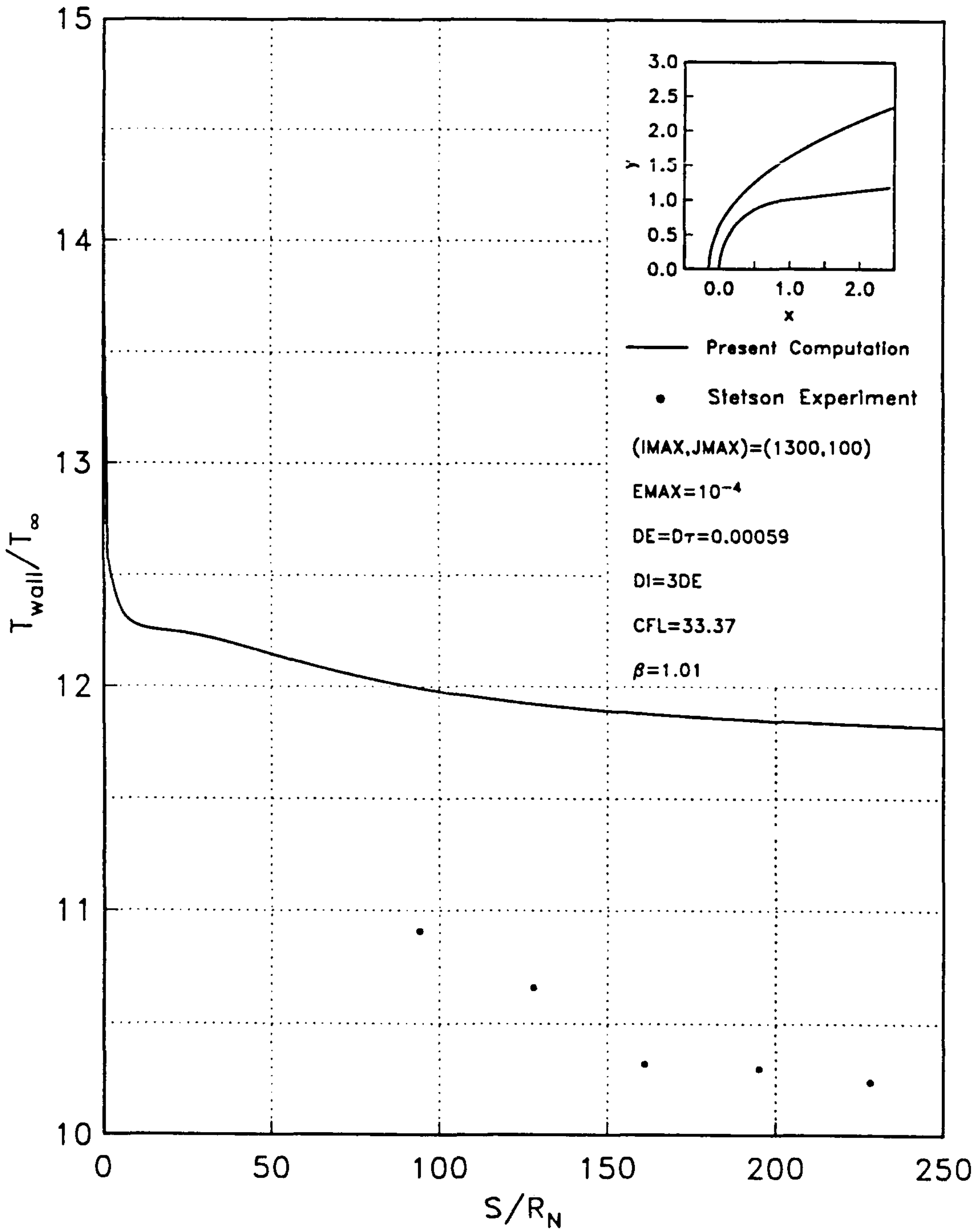


Figure 5. Comparison of velocity profiles for a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3°$ K with experimental data of Stetson et al.

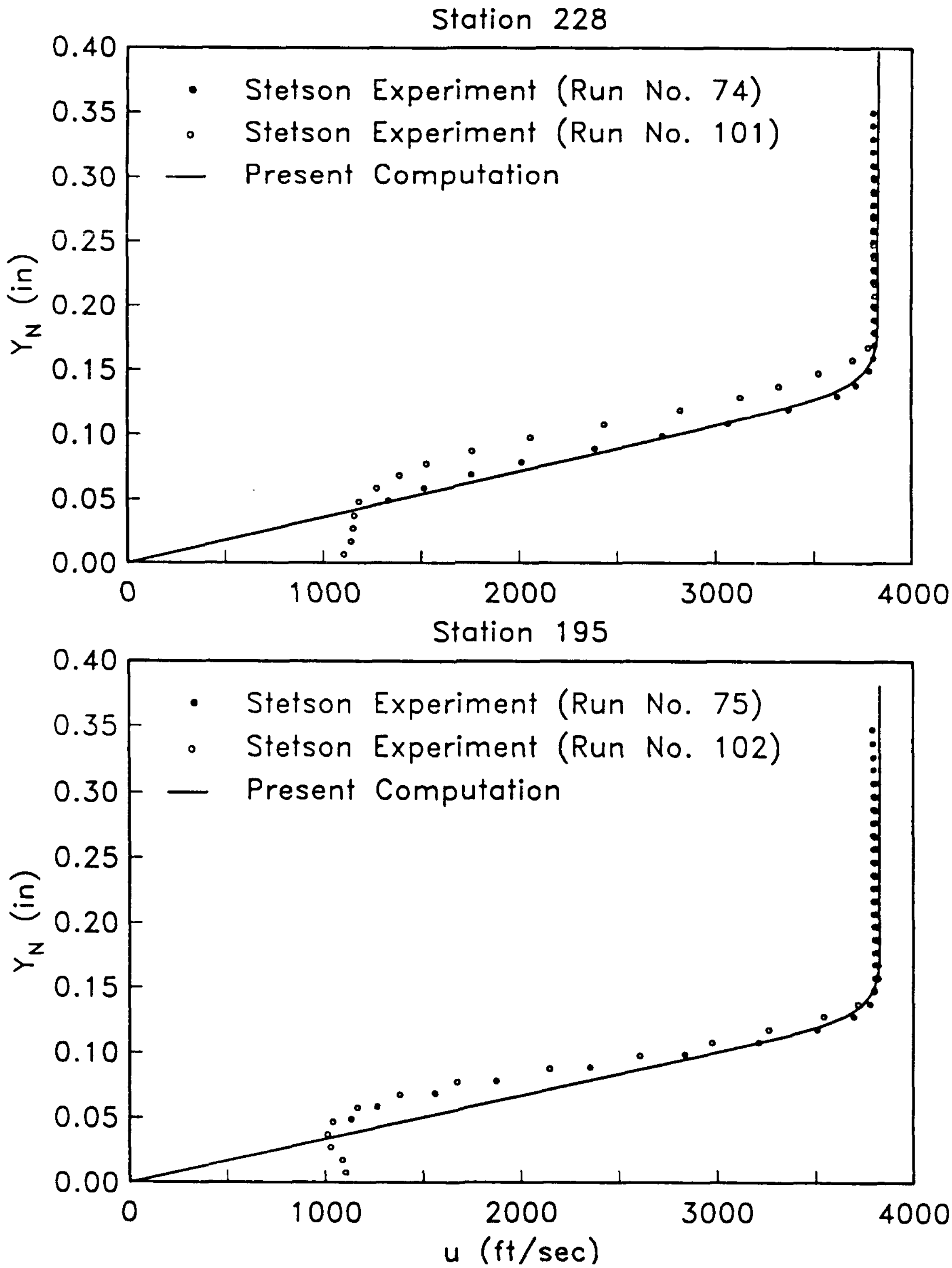


Figure 6. Comparison of calculated and measured spatial growth rates for a 7° blunted cone with adiabatic wall, $M_\infty = 8.0$, $Re_\infty = 31250$, and $T_\infty = 54.3°$ K at station $S/R_N = 175$.

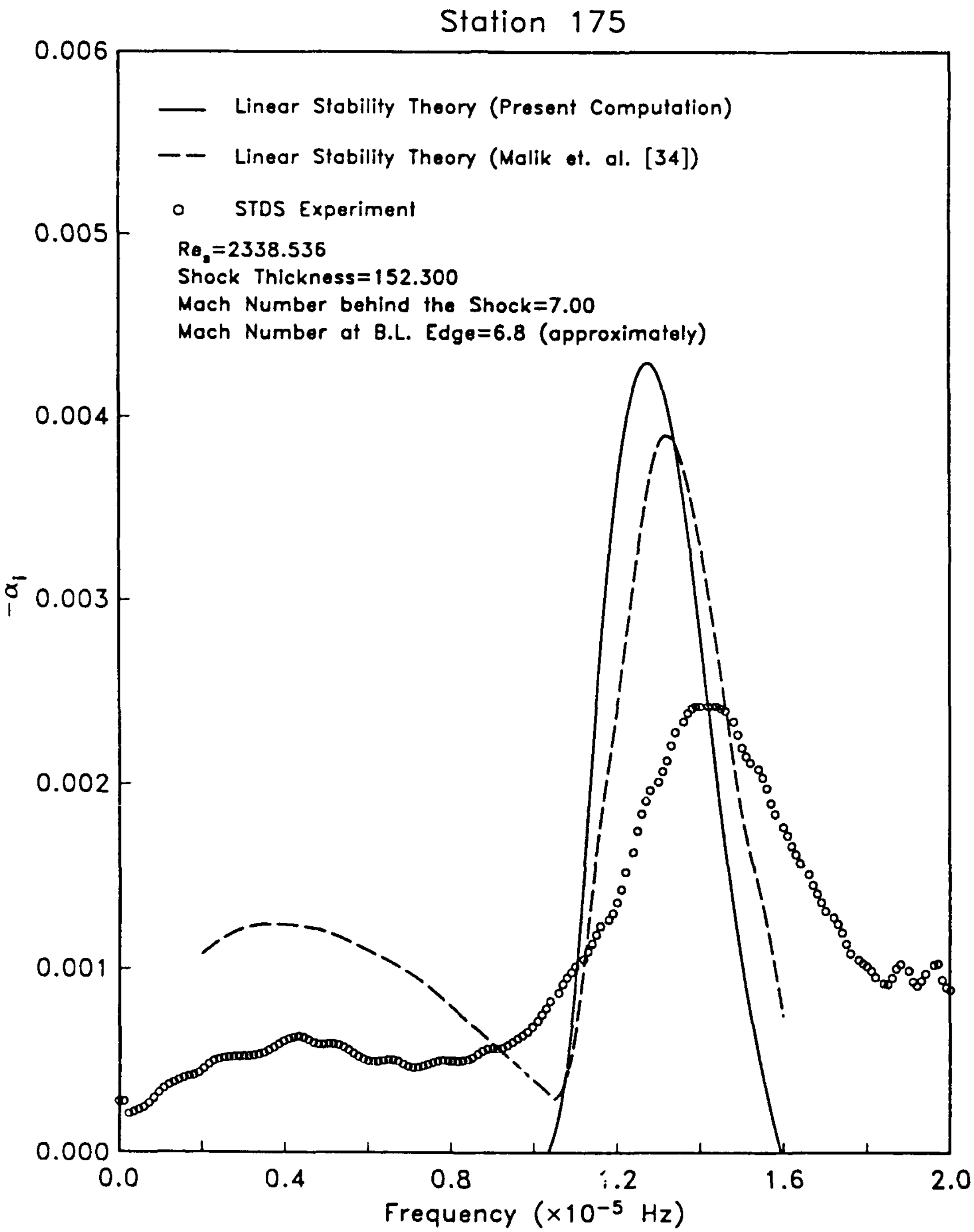


Figure 7. Temporal growth rate vs. wavenumber for the flow on a 5° wedge with adiabatic wall, $M_\infty = 8.0$, $Re = 1557.77$, $T_\infty = 54.3^o$ K, and $y_s = 159.50$ with different boundary conditions at the shock.

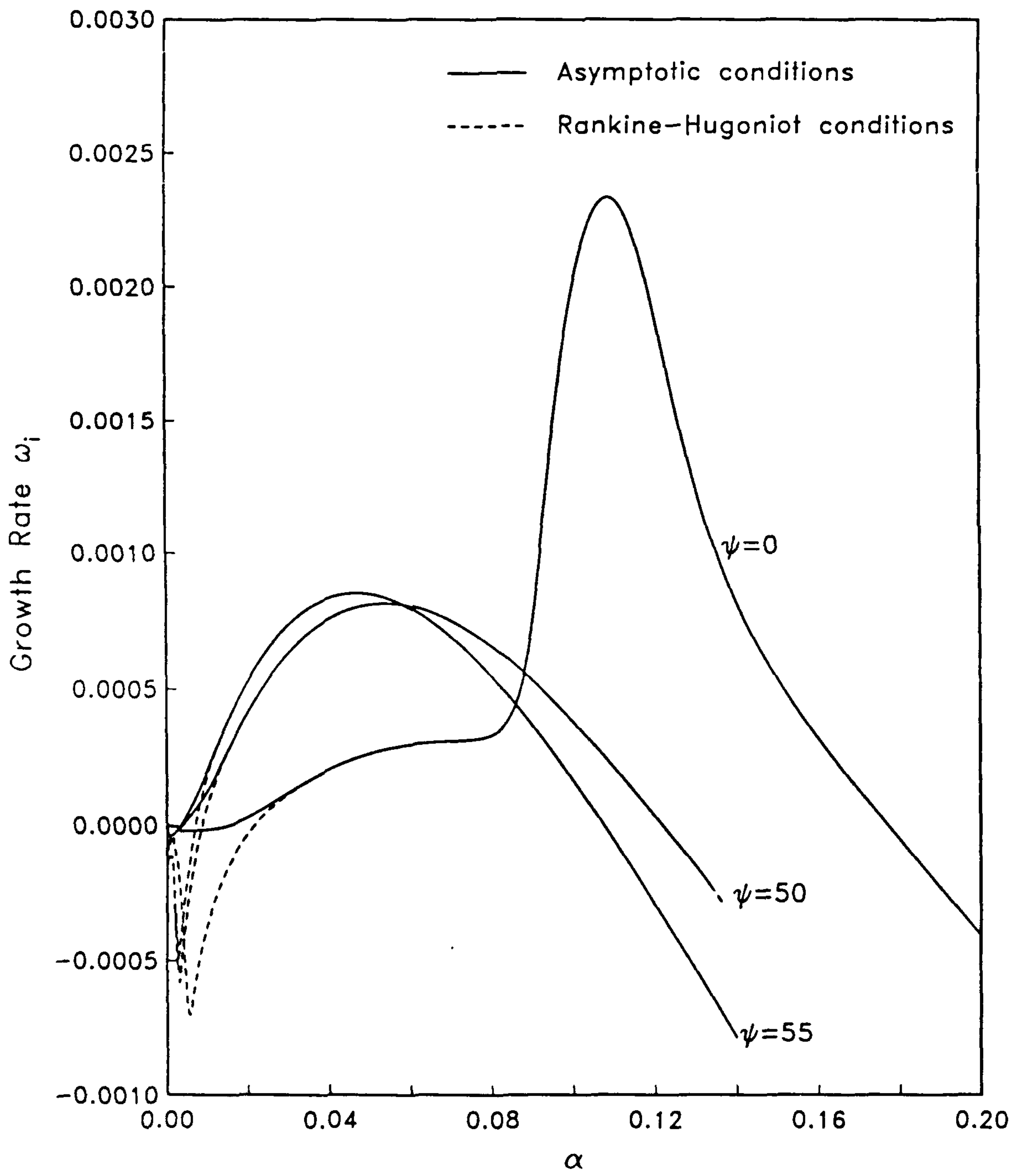


Figure 8. System view of transition, developed in cooperation with M. V. Morkovin.